The Los Alamos Solid-State Optical Refrigerator (LASSOR) Program

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ABSTRACT

Recent work at Los Alamos National Laboratory has demonstrated the physical principles for a new type of solid-state cryocooler based on anti-Stokes fluorescence[1]. From our laboratory work and computer simulations we estimate that a practical, first-generation, all-solid-state fluorescent cryocooler will have the following properties[2]:

- no vibrations
- will not produce and is not susceptible to
     electromagnetic interference
- cool to 77 K
- be ~1% efficient (DC power to cooling power)
- weigh less than 3 kg/Watt
- have a lifetime of 10 years continuous operation.

This first-generation cryocooler will employ material with demonstrated fluorescent cooling capability (ytterbium doped ZBLANP). In this paper we will present the current status of our work including the measured temperature dependence of the fluorescence and absorption for Ytterbium in ZBLANP, the model predictions for the temperature dependence for several hosts, and the current prototype design and component analysis.

INTRODUCTION

BACKGROUND - Anti-Stokes fluorescence is the phenomena in which a substance that is excited by radiation at one wavelength fluoresces at a *shorter* wavelength. This results in more energy being radiated than being absorbed for each photon. Utilizing this process for cooling may, at first, appear to violate common sense: a multi-watt laser is focused into a mostly transparent material, and the material cools. A closer look at a specific cooling process shows how fluorescent cooling works. Consider a glass doped with a rare-earth ion that has broad ground and excited states (Fig. 1). Each broad energy state or manifold consists of several closely spaced energy levels that are in thermal equilibrium among themselves (since we will be discussing glasses the energy levels are actually inhomogeneously broadened bands but for simplicity we will refer to them as discrete levels). When ions are radiatively pumped from the top of the ground-state manifold to the bottom of the excited-state manifold (process 1), the thermal equilibrium in each manifold is upset. The upper level of the ground-state manifold is underpopulated and the lower level of the excited-state manifold is overpopulated. Both manifolds quickly return to equilibrium by absorbing phonons (heat) from the surroundings (process 2). At some later time the ions de-excite by emitting photons (process 3). The fluorescent photons remove both the pump photon energy and the absorbed phonon energy from the system. The net result of this process is the removal of heat from the material.
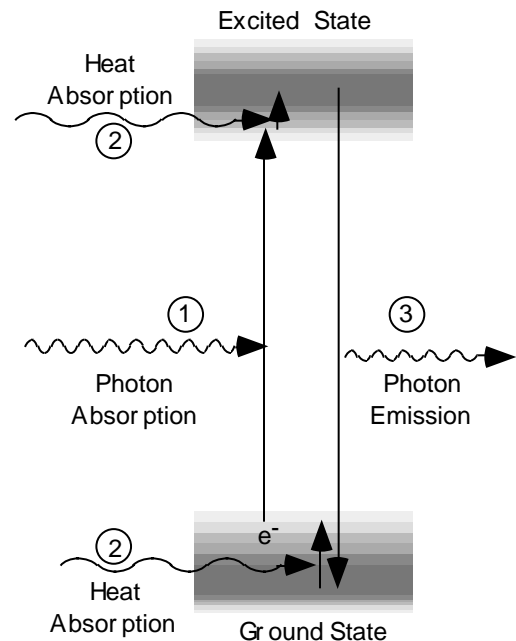
Figure 1: A diagram of the atomic processes that produce fluorescent cooling. 1) Electrons in the upper levels of the ground-state manifold are pumped to the lower levels of the excited-state manifold. 2) The populations of the energy levels re-equilibrate through phonon absorption. 3) Fluorescent photons (more energetic than the pump photons) are emitted as the ions de-excite back to the ground state. Each phonon absorption extracts heat from the system.

In the ideal case, where there are no nonradiative relaxations from the excited- to the ground-state manifolds, there will be one fluorescent photon for each pump photon and each fluorescent photon carries off, on the average, thermal energy equal to the difference between the pump photon

energy and the mean fluorescent-photon energy. The fluorescent cooling power, P_{cool}, is thus proportional to the absorbed pump power, P_{abs}, and to the average difference in the photon energies of the pump and fluorescence radiation. In terms of wavelength, the cooling power can be written as

$$P_{cool}(\lambda) = P_{abs}(\lambda)(\lambda - \lambda_F)/\lambda_F, \qquad (1)$$

where λ is the wavelength of the incident pump radiation and λ_F is the wavelength corresponding to the mean of the fluorescent photons energy.

PRACTICAL MATERIALS - The two essential requirements for a fluorescent cooling material is that it exhibit anti-Stokes fluorescence and that the resulting radiation-induced cooling is not severely degraded by heating from nonradiative decays. Both of these requirements are well satisfied by high-purity ZBLANP:Yb^{3+}.

The Yb^{3+} ion has a simple energy level structure consisting of only a ground-state and a single excited-state manifold at ~1000 nm. The room temperature fluorescence and absorption spectra of ZBLANP:Yb^{3+} indicate that anti-Stokes fluorescence is achievable with this material. Since the mean energy of the fluorescent photons is at λ_F = 995 nm, whenever the excitation is pumped with radiation where $\lambda >$ 995 nm, the glass cools (see Eq. 1). The absorption spectrum shows that it is indeed possible to pump ZBLANP:Yb^{3+} at these long wavelengths.

The absorption and fluorescence spectra vary with temperature since they depend on the excitation populations of each level in both manifolds. At low temperatures the populations of upper energy levels of the ground-state manifold decrease thereby reducing the absorptivity at long wavelengths. This lower absorptivity implies that a longer absorption length or higher doping is required to absorb the same amount of pump power. Similarly, the decrease of the population of the upper levels of the excited-state manifold at low temperatures reduces the fluorescence at short wavelengths. This moves the the mean fluorescence energy to longer wavelengths. In Yb^{+3} doped ZBLANP the shift is from 995 nm at room temperature to ~1003 nm at low temperatures.

The result of the absorption and fluorescence changes observed is that at some temperture it becomes impractical to produce fluorescent cooling with current designs. Additional work on hosts, dopants, and designs are required to achieve lower temperatures and higher efficiencies.

FIRST-GENERATION FLUORESCENT CRYOCOOLER

If the knowledge of anti-Stokes fluorescence and the initial laboratory measurements[1] are to be utilized for cooling in a practical system numerous design issues along with the application requirements must be considered.

OVERALL DESIGN - An especially interesting application of a solid-state fluorescent cryocooler is for use in space where performance attributes are critical. In these applications fluorescent cryocoolers would be a valuable asset because they could be vibration-free, low-mass, rugged, long-lived and efficient.

Figure 2 illustrates one design for a fluorescent cryocooler that might be used for space applications. This design is based on using ytterbium (Yb^{3+}) doped heavy metal fluoride glasses for the fluorescent cooling element. Preliminary studies have demonstrated that one such material, ZBLANP:Yb^{3+}, is an effective fluorescent cooler[1].
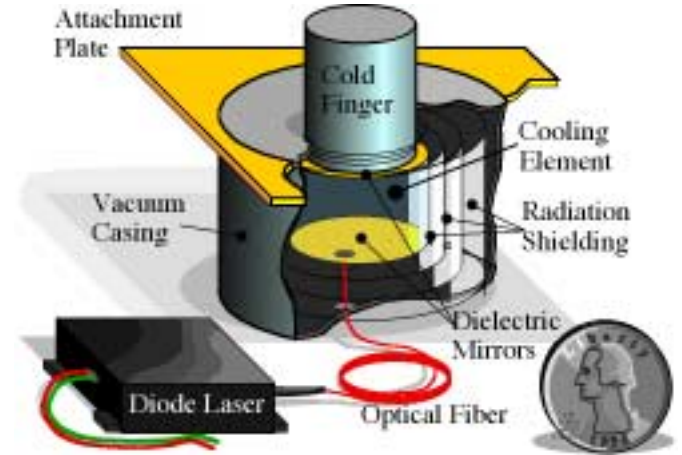

Figure 2: A possible realization of the LASSOR. Pump light from a diode laser is trapped between the two mirrored faces of the cooling element. The escaping fluorescent radiation is absorbed on the vacuum casing.

Our initial design utilizes diode lasers coupled with an optical fiber to deliver the required pump radiation (see Fig. 2). The fiber carrying the pump radiation passes through the wall of the cryocooler and to a cylindrical block of ZBLANP:Yb^{3+}, the cooling element at the heart of the device (see Fig. 3). Dielectric mirrors that reflect the pump radiation are deposited on both ends of the cooling element. The pump radiation enters the cooling element through a small hole in one of the mirrors. The pump radiation is largely beamed along the axis of the cylinder and is repeatedly reflected from the dielectric mirrors and from the sides of the glass cylinder (by total internal reflection). Ultimately, the pump radiation is absorbed by Yb^{3+} ions, and the doped glass cools as it fluoresces. Most of the isotropic fluorescent radiation escapes from the cooling element and is absorbed by the warm walls of the cooling chamber. On the back of one of the dielectric mirrors will be attached a transparent connection and metal mirror to create a completely shadowed region where the cold finger can be attached.

Each of the components of the fluorescent cryocooler must be precisely combined to produce an effective device. For a more detailed discussion of the basic design see Edwards, et al. 1995.

STATUS OF DEVELOPMENT PROGRAM - Work on the development of fluorescent cooling for practical applications has primarily concentrated on the evaluation and improvement of the cooling material. The work has produced additional glass sources and improved evaluation techniques.

We have produced fluorescent and absorption curves for Yb doped ZBLANP at temperatures from 2 to 300 K and begun cooling tests at temperatures below 300 K. The results from these initial tests do not disagree substantially with what is expected. Bulk samples have also been produced for trapping the light and are being tested at temperatures below 300 K.

CONCLUSIONS

Laboratory data has proven the feasibility of cooling macroscopic, solid objects by anti-Stokes fluorescence[1]. We have studied the possibility of using this phenomenon to produce a practical cryocooler[2]. With current technology a fluorescent cryocooler that generates ~0.5 watts of cooling at 77 K seems feasible[2]. This paper reports on progress toward producing a efficient cooling at temperatures below 300 K.

REFERENCES

1. Epstein, R. I., Buchwald, M. I., Edwards, B. C., Gosnell, T. R., and Mungan, C. E., *Nature*, October 14, 1995, pp. 500-503.
2. Edwards B., Buchwald M., Epstein R., Gosnell T., and Mungan C. E., <u>Development of a Fluorescent Cryocooler</u>, *Proceedings of the 9th Annual AIAA Conference on Small Satellites*, Logan, Utah, September, 1995.